POWER LINE MODEL FOR TESTING TRANSIENT RESPONSE OF PMU

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Abstract - In the "Relay Protection" laboratory of TU-Sofia power line physical model was adapted for testing of PMU, with target to demonstrate the students PMU and multifunctional Intelligent Electronic Device (IED) functionality. Another target was to improve the student's skills to make oscilloscope records of signals and to compare with IED/PMU obtained data. The model scheme general characteristics and the approach of PMU function demonstration are presented in the paper.

Keywords - PMU, IED, test, power line, model.

I. INTRODUCTION

The Phasor Measurement theory and respectively the Phasor Measurement Unit (PMU) application became possible in the engineering practice as result of the rapid advance of the microelectronics and space technologies in the end of the XX-th century [1]. The application of PMU modules as sources of accurately measured and time stamped data allowed the realization of WAP (Wide Area Protection), WAM (Wide Area Measurement) and other related functionalities [2,3,5]. In result of the swift generation of new electronic devices families, dedicated for electrical power grid application, the preparedness of the potential equipment operator stands sometimes slightly behind the "news". Inertia in the thinking can be observed from different points of view - both as positive and negative approach, but for the case of PMU application, definitely limits the ability to take advance of new technologies. In some cases, power system operators mix Supervisory Control and Data Acquisition (SCADA) with the advanced PMU based solution for distributed data sampling with time stamping "at the point".

For commercial application the PMU function is subject to test with precise laboratory equipment [4,6]. PMU sourced data for voltage and current phasors, values of active, reactive, apparent power; phase angles, harmonic content, etc., shall be verified. The verification of the PMU sourced data shall be precisely estimated as absolute value, phase angle, time stamping etc.

Precise test of PMU and verification of acquired data is obligatory for TSO / utility applications. For laboratory experiments and in particular demonstrations for students and experimental records of transient phenomena, laboratory models with not such straighten accuracy requirements can be used. The concept of the presented in the paper model is also based on the requirement of potential employers for extended knowledge of the future specialists in the area of measurements, process registration and data analysis [7,8,9,10].

II. DESIGN FEATURES

The transient phenomena can be described as rapid change of the parameters of the scheme, which can simulate short circuit, change of load, longitudinal fault (open circuit). The basic theoretical relations for simulation of short circuit are presented as follows: the momentary current, modeled to be the hypothetical short circuit current is assumed as sum of the periodic and direct (DC / aperiodic) components:

$$i_{SC}(t) = i_p(t) + i_{DC}(t) \quad (1)$$

The periodic component can be expressed as:

$$i_{pt}(t) = \frac{V_m}{Z_{SC}} \sin(\omega_0 t + \alpha - \varphi_{SC}), \quad (2)$$

$$i_{pt}(t) = I_{pm} \sin(\omega_0 t + \alpha - \varphi_{SC}), \quad (3)$$

where:

V_m is the model supply phase voltage peak value,

Z_{SC} is the impedance of the circuit after fault occurrence,

α is the voltage initial phase angle,

φ_{SC} is the angle characterizing the X/R ratio of the modeled fault circuit.

The DC component can be expressed as:

$$i_{DC}(t) = \left[I_m \sin(\alpha - \varphi) - I_{pm} \sin(\alpha - \varphi_{SC})\right] e^{-\frac{1}{Q}.t}, \quad (4)$$

where:

$$Q = \frac{L_{SC}}{R_{SC}} \quad (5)$$

I_m, φ – the parameters characterizing the initial circuit – prior short circuit occurrence.

The peak value of the fault current is defined by the maximal possible momentary value of the periodic and DC component, coinciding in polarity. For electrical circuit the coincidence by sign is obtained in case of $\alpha - \varphi_{SC} = \pm 90°$ and $\alpha - \varphi = 0°$.

The option to set the model parameters to obtain desired $\alpha, \varphi, \varphi_{SC}$ allows simulation of particular cases of transient process.

The model has been designed for simulation of transient process typically to estimate the response of the protection / grid automation devices in case of short circuit. The scheme allows the study of transient process effect on the measurement accuracy, delay, selectivity, etc. The model has 3 phase stricture in order to allow modeling of all type of faults.

The impedances of the power supply source (the "grid connection") and the power line can be modeled with set of resistive and inductive elements. At this stage capacitive element has not been used. The model has been intended as first priority to model overhead power lines.

The scheme of the model is presented in Fig. 1. The supply voltage is applied at terminals R, S, T, 0. Prior to energizing, the adjustable impedances Z_S and Z_L shall be set to the respective "Source" and "Line" impedances. Between them two CTs per phase are installed and the functional switch SF, which is used for realization of the respective transient simulation. The power is switched-off with the grid contactor CG. For ground-fault simulations the impedance Z_{LN} has been foreseen in the model design. The voltage transformers (VT) can be connected on both sides of the functional switch S_F. The mode switch S_M allows selection of fault mode and shunts for direct measurement of current. The bridges for connections can be used to tackle oscilloscope current probe.

The commutation control of the phase S_F and C_G defines the initial moment (voltage angle α) of the supply voltage, the process duration and registration of signals. Control signals are used also for external oscilloscope trigger (if level trigger in not used) and eventually for connection to PMU/IED binary input.

The model design allows simulation of different fault cases - phase to earth, phase to phase, with or without ground impedance/ at different impedance of the supply grid. The DC component decrement time constant can be varied by change of the X/R ratio. For test of IED - in particular with impedance function, the impedance values simulating short circuit on the power line can be simulated. PMU can be connected at the points for IED connection or in other points with additional CTs.

The impedance Z_S which represents the power source is realized with coils without cores (linear inductive elements). By different connections of the elements 24 values can be obtained in the range from 2 to 144 Ω (the values are presented in Table 1, Table 2). In Table 1 are presented values achievable by series connection of elements. In Table 2 are presented values achievable by parallel connection of elements.

Table 1

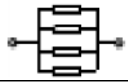
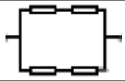
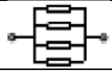
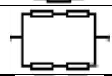
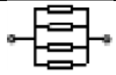
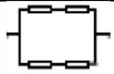
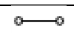
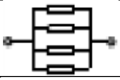
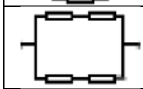
12Ω / 24Ω				
	0	3	12	48
	0	9	18	54
	24	27	36	72
	96	99	108	144

Table 2

12Ω / 24Ω				
	0	0	0	0
	0	2	4	5.34
	0	2.6	8	16
	0	2.9	10.8	32

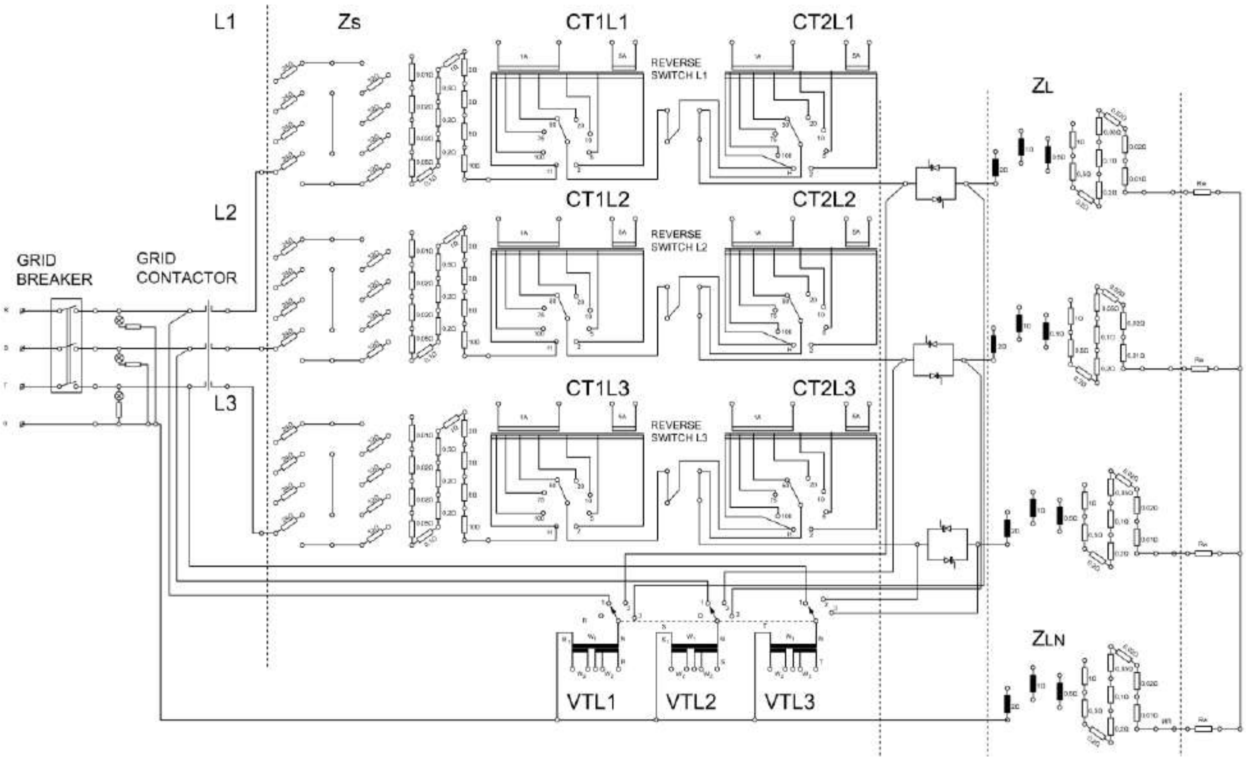


Fig. 1. Model scheme

Using different combinations of element connections, the maximal “grid fault current” capacity is predefined. If Z_L=0 the maximal expected values for U_S=220V are presented in Table 3. For larger currents single phase scheme can be supplied on line-line voltage supply (the third column of Table 3). The recorded values for the power supply voltage in the laboratory can reach up to 240V for close to idle mode operation of the 20/0.4kV power transformer, so for every experiment the particular conditions are assumed and taken into account for the settings calculations.

Taking into account the local grid specifics, experiments were made with ratio of inductive / active component of Q=20. Such case defines a maximal attenuation constant for the aperiodic (direct) component of the transient current Ta = 64 ms. With the additional active resistors R_S, the ratio can be reduced to Q=5, which defines a time constant Ta= 16 ms. This option allows different cases modeling - flexibility for different points located in the power grid simulation.

Table 3

	Z_S	$I_{SC\ max\ Ph.V}$	$I_{SC\ max\ L\text{-}L\ V}$
N	**Ω**	***A***	***A***
1	2	110	190
2	2,6	85	146
3	2,9	76	131
4	3	73,5	127
5	4	55	95
6	5,34	40,6	71,2
7	6	36,8	63,4
8	8	27,6	47,5
9	9	24,5	42,3
10	10,6	20,7	35,9
11	12	18,3	31,7
12	16	13,7	24,8
13	18	12,2	21,1
14	24	9,15	15,8
15	27	8,15	14,1
16	32	6,9	11,9
17	36	6,1	10,2
18	48	4,57	7,92
19	54	4,07	7,05
20	72	3,05	5,28
21	96	3,29	3,95
22	99	2,31	3,84
23	108	2,02	3,52
24	144	1,53	2,64

The induction elements are without core, linear behavior without saturation has been targeted. The resistors are alloy type, designed to have low level of inductance.

The line (Z_L) is modeled also with inductive elements (linear inductances) and resistors. By switching the inductive elements, values can be set from 0,5Ω to 3,5Ω / per phase, with increment step of 0,5Ω. The value Q=10 for the reactive elements can be reduced to Q=1.7 by additional active resistors R_L. In such way power lines with different specific impedance angles can be modeled - from φ_{PL} = 84° /at Q=10/ to φ_{PL} = 60º /at Q=1.7/.

The impedance Z_{LN} can be connected in the neutral circuit and is similar to Z_L, but its values are on the half. Z_{LN} varies from 0,25Ω at increment steps of 0,25Ω to 1,75Ω.

The values for Z_L and Z_{LN} are presented in Table 4.

Table 4

N	X/R = 10	X/R = 2,75	X/R = 1,7
	Z_L	R_L	R_L
1	0,5	0,13	0,24
2	1,0	0,26	0,48
3	1,5	0,40	0,72
4	2,0	0,53	0,96
5	2,5	0,66	1,20
6	3,0	0,80	1,44
7	3,5	0,92	1,68
N	X/R = 10	X/R = 2,75	X/R = 1,7
	Z_{LN}	R_{LN}	R_{LN}
1	0,25	0,07	0,12
2	0,50	0,13	0,24
3	0,75	0,20	0,36
4	1,00	0,26	0,48
5	1,25	0,33	0,60
6	1,50	0,40	0,72
7	1,75	0,47	0,84

Per each phase two current transformers (CT) are foreseen. The reverse switch scheme allows testing of differential function as well. The voltage transformers (VT) can be switched to both side of the functional switch.

Practically the model can be used in different modes:

– With one PMU module, in order to compare data acquired by PMU with oscilloscope records;

– With two PMUs in order to compare the data between them. Preferably the PMUs shall be identical, with identical (common) GPS signal source. If PMUs provided by different producers are utilized, preferably a common antenna / GPS signal receiver shall be used.

– With one PMU module and IED. The PMU can be used as IRIG-B source or other applicable protocol for synchronization of the IED.

To avoid time lagging errors, length of antenna cables to different PMU shall be equal, with equal cable types.

The PMU/IED obtained data can be compared with the theoretically calculated. One important precondition for correct recognition of the sampled signals is the status of power supply parameters. The designed model was tested with 3L 0.4kV mains power supply, but some harmonic errors occurred. The analysis of the grid supply indicated that the mains voltage has shape distortion close to the peak of the voltage sine. The problems were related to the 20/0,4kV transformer for the lab building. Option for future experiments is to use grid independent generator with sine voltage or power supply unit for circuits testing, with limited THD.

III. EXPERIMENTAL RULES

The preliminary experiments performed with the model were organized in accordance to the following steps:

- Calculation of the expected transient process (example of a pre-calculated experiment is presented in Fig. 2.);
- Set of the necessary values on the model;
- Safety measures for check of connections / securing the facility / limiting access to live parts;
- Model energizing and recording of the transient process parameters;
- Model de-energizing;
- Data download;
- Analysis of the acquired records.

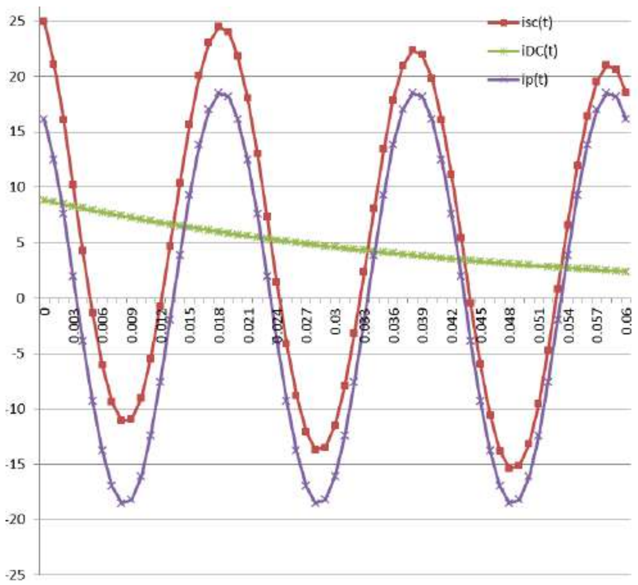


Fig. 2. Expected pre-calculated transient process

IV. RESULTS

The recorded data sourced in *.CSV (coma separated values) file format has been compared in MS Excel. The target of the data analysis was to estimate the deviation between the expected (preliminary calculated) process and the recorded data. The scheme presented in Fig. 4 depicts the exchange of signals. In case of IED connected to the measurement points in the model IRIG-B signal was used from the PMU for synchronization.

The practical experiments performed by students resulted in increased interest to the PMU technology, as the theoretical basis can’t give sufficient visual impression for the benefits of the “on-line” synchronized measurement. The continuous recording of the grid frequency measured value presented in Fig. 5 and Fig. 6 were excellent demonstration for the permanent fluctuation of the grid frequency.

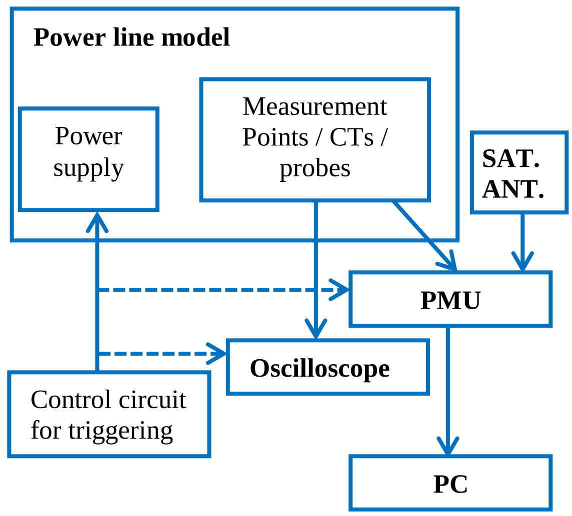


Fig. 3. Exchange of signals

The model shall be further improved towards implementing microprocessor control circuit for precise adjustment of the initial voltage phase angle. For the current state of the facility some additional calculations were necessary in order to adopt the calculated (theoretically) values of the transient to the practically applied voltage angle α. the Experimental record with oscilloscope of transient is presented in Fig. 5.

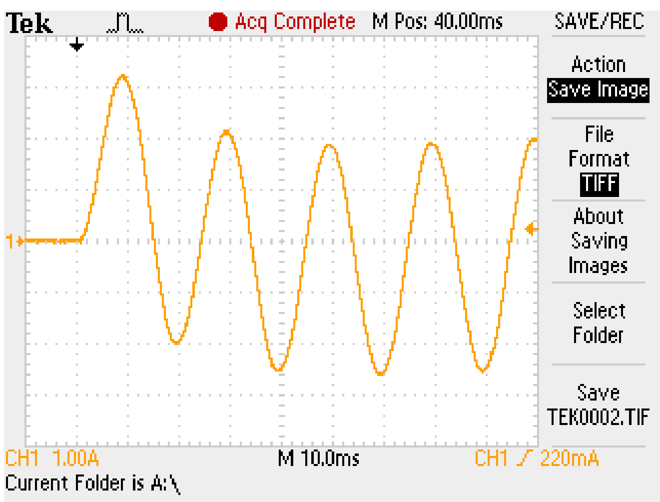


Fig. 4. Record of transient process

In aspects of model operation the work results indicated, that increased caution shall be expected from the operators. For safety reasons and in order to provide galvanic separation the oscilloscope recording of the current wave was made with "clip-on" clamp current probe. The PMU module voltage signal inputs were directly connected to the model.

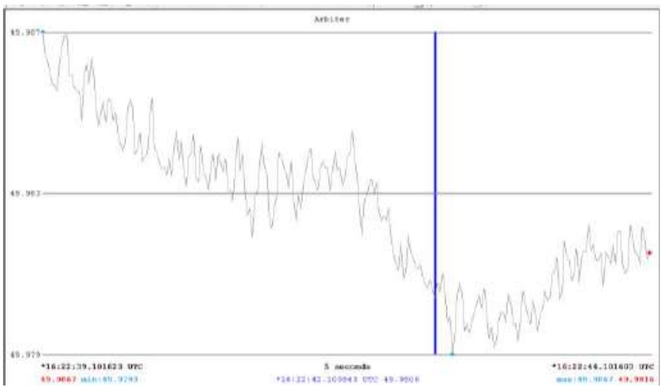


Fig. 5. PMU module frequency record

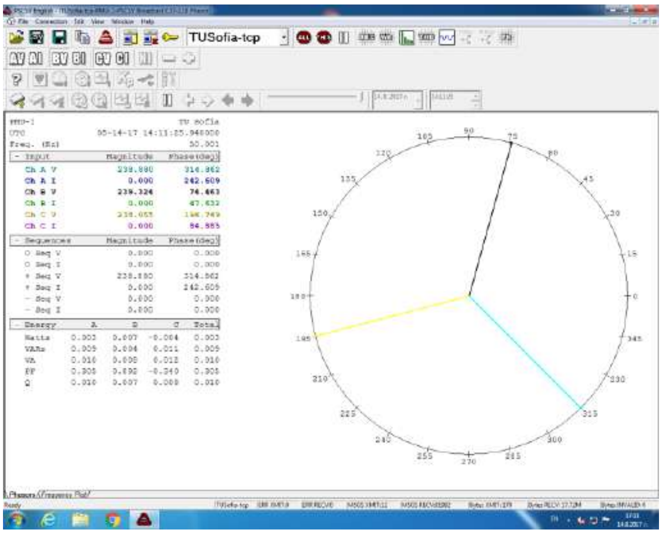


Fig. 6. Voltage record at lab site

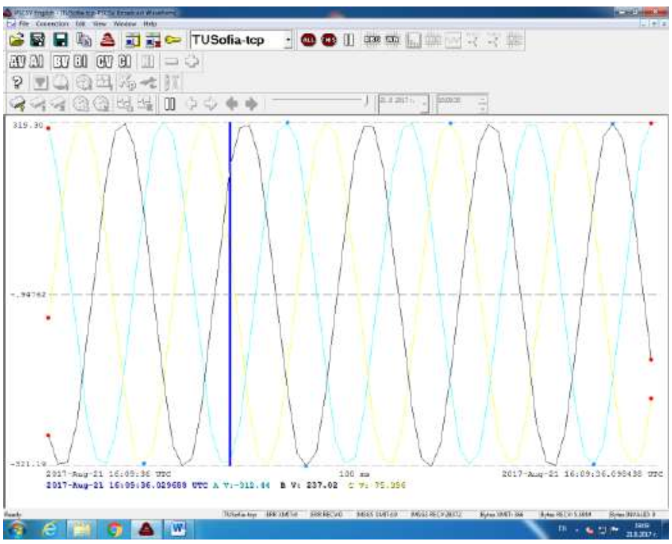


Fig. 7. Recorded waveforms

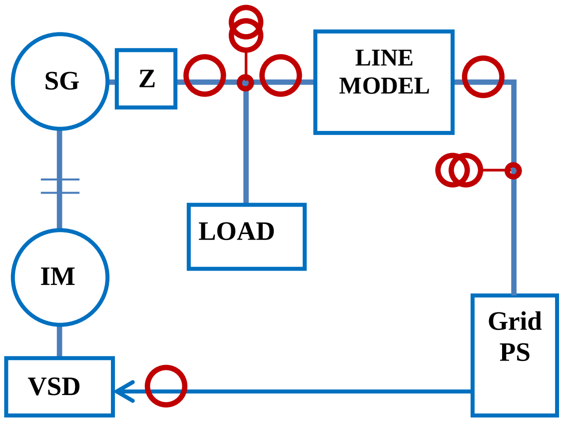


Fig. 8. Physical model extension with motor-generator group

Preliminary tests of the installed PMU were used for the demonstration of the synchronized measurement technology to the students specializing in the area of the electrical power systems. The PMU acquired data recorded on PC based PDC was used for experimental analysis and comparison with test scheme parameters and oscilloscope records.

Further extension of the model will be made with installation of grid protection IED with PMU function. Further model extensions for simulation of grid disturbances registration is planned with several measurement points scheme. The commonly time-stamped signals, measured with a multi input IED with PMU functionality will help better simulation of grid transient phenomena. In Fig. 8 is presented simplified concept scheme, the measurement points are symbolically marked with symbols for CT/VT. The Variable Sped Drive (VSD) for the Induction Motor (IM) – Synchronous Generator (SG) group via software control will allow different grid disturbances to be experimentally simulated.

Another target is installation of PMU in different university, located in remote part of the electrical power grid, to be realized. For the moment the PMU module has been left to record data for the grid voltage available in the laboratory.

V. CONCLUSIONS

The model allows a physical test, involving students in preliminary calculations of the transient process, preparing and actuating the test scheme, performing records with digital oscilloscope and PMU unit. Typical experiment is calculated values to be compared with recorded experimental data and estimation of the specifics of the transient process is made.

The laboratory power supply voltage recorded data in respect of frequency values is applicable for the grid operational state.

One of the goals of the demonstrations for students is also the physical phenomena mathematical representation to be analyzed correctly. The formulas (2-4) are related to sine shape assumed signals. Actually the grid processes are assumed to be sine-shaped, but even during normal operation the presence of harmonics shall be taken into account. In particular for transient process besides the primary currents / voltage signals distortion (DC components in result of faults, “fast” transients related to commutations, oscillations, impulses caused by lightning strikes) the impact of the measurement transducers (instrumental transformers – CTs, VTs) shall be counted.

For the performed preliminary experiments the measured values indicated some mismatches between oscilloscope and PMU data. The mismatch can be explained with the different primary sensors: Hall Effect based current probes for oscilloscope and CTs for the PMU. For registration of the front edge picture of fast transients CTs will play negative role, as may filter out the higher harmonics and respectively distort the process secondary signal. Hall Effect sensors or Rogowski coil sensors may fit better in transient process registration [19,20,21].

For practical application of the PMU functionality correctly, the type of the CTs shall be taken into account [14,15,16,18].

The parameters of instrumental transformers may provide “accurate picture” of secondary signals for stable-state grid operation modes, but may reject or distort part of the “details” in the secondary signals in primary circuit transients. The PMU function for power metering needs high accuracy in the rated load diapason, and the fault / transient registration would need CT core designed for relay protection applications. If power metering function is used for the PMU, the respective CT measurement core may fail to give accurate secondary signals in case of sensing primary short circuit currents. During grid faults power quality indices measurement is problematic, but the short circuit current measurement accuracy will help for the fault event analysis. The inputs of PMU modules have low impedance resulting in low CT burden [13,16], but application of alternative measurement sensors like Rogowski coil or for some specific cases Hall-effect based sensors may help to obtain better fault data record in normal operation and during transients as well. Most industrial type IEDs, PMUs and PMU based are typically equipped with conventional instrumental tr-s inputs. The respective analog input signals, compatible with alternative sensor types shall be used for wide range signal frequency, respectively for accurate data acquisition for transient processes.

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